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PALEOCEANOGRAPHIC EVIDENCE OF CLIMATE CHANGE IN THE CANADIAN ARCTIC: THE PAST 10,000 YEARS

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ABSTRACT

The reduction, and ultimately the disappearance, of sea ice enhances the warming response of high latitude oceans through a positive feedback loop related to lessening of the heat reflected from ice. In theory, the more sea ice melts, the more rapidly the Arctic will warm. Computer models predict that continued global climate warming may lead to a temperature rise of 7.5ºC and ice-free Arctic water by 2100 AD, but they are deficient in accuracy of sea ice predictability. Paleoceanography uses fossil plankton that are tuned to modern sea surface temperatures, salinity and ice cover to reconstruct prehistorical changes for known times of climate conditions that were warmer and colder than now. The results of these paleoceanographic studies are used to test the validity of the climate models. Research using BIO vessels in the Canadian Arctic was on the forefront of development of using sediment archives and dinoflagellate cysts to reconstruct changes in arctic temperature and sea ice over the past 10,000 years. The most recent research reveals east-west swings in records between Beaufort Sea and northern Baffin Bay that may allow refinement of earlier paleoclimate models for the whole Arctic region.

DRIVING ISSUES: CANADA's CHANGING CLIMATE

Climate change! Global warming! These expressions are now part of Canadian concerns, from Eureka at the northern tip of Ellesmere Island, to the Canadian/USA border, and the topics has been the focus of scientists, government agencies and the general public for over three decades. Titles such as "Is humanity occupied with influencing the climate of the world?" (Van Zuylen 1973) began appearing in the scientific literature as early as the 1970s. The scientific community is concerned with understanding the mechanisms of climate, the interactions between the many variables involved, including the role of Humans in post-industrial times, while the government agencies and general population are concerned about how to adapt and eventually reduce the Human impact on such changes.

Thus, climate change has become as much a scientific issue as a societal issue. To this effect, the government of Canada and those of numerous countries around the World have allocated special funds to address the various issues involved, with BIO taking an early lead in studying the impacts of rising temperatures in the Arctic (see Chapter by Mudie et al., this book). The Canadian scientific community could count on the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) and the Natural Science and Engineering Research Council of Canada (NSERC), among others, to support scientific research on various aspects of present, past and future climate change. Vast international multi-disciplinary programs were also launched to gather data from all continents and put together a global perspective on climate change. The most recent Canadian scientific programs include, the Canadian Arctic Shelf Exchange Study, ArcticNet and the Canadian contribution to the International Polar Year, within which the

Geological Survey of Canada Atlantic (GSCA) played a major role in the study of the prehistorical and geological aspects of climate change.

One of the most salient feature of Earth's history is the ever changing state of climate ever since its formation 4.5 billion years ago, from glaciations as early as 2.9 billion years ago (Young et al. 1998), to warmer than present conditions (by ~4ºC), such as during the Cretaceous Period, about 200 million years before Humans evolved. Most recently, the Quaternary Period (2.6 million year ago to Present) was characterized by a series of cold glacial intervals each lasting 100,000 years, alternating with warm interglacial intervals lasting 10-15,000 years. These changes are driven by slow, steady variations of the Earth's astronomical orbital parameters, eccentricity (ca. 100,000 year cycle), obliquity (41,000 years) and precession (21,000 years), all of which modulate the insolation (energy) received from the sun.

The present interglacial, the Holocene epoch (past 10,000 years BP, or 11,700 cal BP), also experienced these natural, slow climate changes, but it is notable for some differences that have been ascribed to the activity of Humans (*Homo sapiens*), who first appeared in Asia about 80,000 years ago. According to the astronomical theory, the Earth received maximum insolation from the sun about 9000 years ago, and we should now be cooling down toward the next glacial period. Recent studies based on ice core and sediment records suggest that the next glacial inception should be within the next 1500 years, providing that atmospheric CO_2 concentrations did not exceed pre-industrial levels (Tzedakis et al. 2012). But anthropogenic production of greenhouse gases has potentially disrupted this natural cycle, and in the eastern Canadian Arctic, this factor is thought to be the reason that icecaps are retreating, not expanding (Ruddiman 2003).

In addition to changes induced by orbital parameters, climate is the result of complex interactions between the atmosphere, hydrosphere and cryosphere occurring at different timescales: annual, decadal, secular and millennial. Instrumental records and historical archives provide some answers for the first three timescales. However, important changes take place at the millennial timescale and they cannot be addressed with the available instrumental data. This is where the climate archives preserved in ice sheet cores and marine sediments will provide long time series and make up for the lack of instrumental data. Marine sediment cores are particularly valuable for understanding prehistorical changes in Arctic sea ice and associated changes in ocean water masses.

Arctic paleoenvironmental reconstructions: Why are they so important? Instrumental data indicate that the global average temperature has increased by 0.74ºC between 1906-2005, and the warming trend has nearly doubled between 1956 and 2005 (~0.13ºC per decade). In the Arctic, however, the warming trend has been doubled that of the global average for the period 1906-2005 (IPCC 2007). This trend is of particular concern because it is associated with thinning and shrinking of sea ice, leading to larger amounts of summer open water that allows more heat to be absorbed by the surface water, thus potentially accelerating the ice thinning. Continued greenhouse gas emissions at the current rate during the 21^{st} century are predicted to induce changes larger than those observed during the 20^{th} century. According to modeling experiments, the global average temperature will warm between 0.6 - 4ºC within the next century, but in polar regions, the predicted warming can be as much as 7.5ºC (IPCC 2007). Recent studies predict that the Arctic Ocean will be free of sea ice by 2028 in summer (Wang and Overland 2009).

Among the many variables that are considered to construct these future climate scenarios, sea ice extent and thickness are among the most difficult to predict. This is reflected in the wide range of model responses to sea ice decrease presented by the Intergovernmental Panel on Climate Change (IPCC 2007). Sea ice measurements and satellite data for the Arctic since the late 1970s indicate a reduction in average extent by about 2.7% per decade, with a more pronounced reduction in summer (7.4% per decade on average). But sea ice is melting faster than predictions, with the years 2007 and 2011 being the lowest on record in terms of ice extent (NASA 2011). Because climate models are relatively inefficient at modeling sea ice, however, alternative ice indicators are necessary to verify and improve the accuracy of the results. The best alternative to that problem is the use of quantitative paleoenvironmental reconstructions to provide long time series of various environmental variables, like sea surface temperature and duration of sea ice cover. Among the many paleoenvironmental proxies used in paleoceanography, very few are suitable for the reconstruction of sea ice on a quantitative basis.

FINDING THE RIGHT TOOL FOR THE JOB

Marine sediments of the Arctic contain an array of climate proxies that provide information on various parts of the water column (surface, middle, bottom), as well as global climate and continental ice volumes. These sources of proxy-oceanographic data include fossil foraminifers, diatoms and dinoflagellates, in addition to the texture and chemistry of the sediments that enclose them.

Foraminifers are unicellular organisms, often with chalky shells, some of which live in the water column, other that live on or in the sediments. Therefore, they provide information on the conditions of the entire water column. Although benthic foraminifera have a relatively high diversity in Arctic environments, the planktonic ones are restricted to a single species, so they cannot provide a diversity of paleoenvironmental proxy-data. Also, Arctic waters are undersaturated in calcium carbonate and the chalky shells are often corroded or completely dissolved (Azetsu-Scott et al. 2010). The information they provide is therefore limited. The sort of problem applies to diatoms, which are unicellular planktonic algae with walls of silica, because most Arctic waters have a low silica content, the walls of most diatoms are very thin and they easily break or dissolve over time. Some diatoms live in brine channels in sea ice and are the starting point of the spring plankton blooms that feed fish and mammals of the Arctic. Both planktonic and sea ice diatoms form highly diversified assemblages in high latitudes but because their siliceous remains are subject to dissolution, their use as paleoenvironmental indicators in the Arctic is limited. Dinoflagellates are unicellular algae that live in the photic layer of the world oceans. The vegetative stage of the dinoflagellate is composed mostly of cellulose and decomposes rapidly after the death of the cells. However, many dinoflagellates form a resting cyst as part of their life cycle, and in response to environmental stimuli. These dinoflagellate cysts are composed of a highly resistant polymer that is acid-resistant and remains well-preserved in sediments for millions of years under appropriate chemical conditions. They form diversified assemblages throughout the Arctic and represent the environmental conditions in which they were formed. Dinoflagellate cysts are the most versatile micropaleontological proxies available in Arctic environments.

Several scientific survey and coring campaigns by the GSCA took place in the Canadian Arctic in the 1970s, 1980s and 1990s. They provided a wealth of baseline information on sediment deposits and their microfossils throughout the eastern, central and western Arctic. Pioneer cruises of CCGS *Hudson* in the 1970s provided good sample coverage of Baffin Bay shelves and deep water basins, establishing that many of the deep water sites contained long gravity flow mud sequences and very short Holocene sections that could not provide detailed records of the most recent climate changes (Aksu 1983; Praeg et al. 1985). However, the samples established the presence of dinoflagellate cysts and pollen in the arctic marine samples and allowed initial analysis of the degree to which the fossils recorded the modern-day environmental conditions (e.g. Mudie 1982). In the 1980s, more samples were collected under the permanent pack ice of the Canadian polar margin from the Canadian Ice Island (see Chapter **X**, this volume) and new collections were made in Beaufort Sea that allowed comparison of the impacts of Mackenzie River discharge versus that of Russian arctic rivers (Matthiessen et al. 2000; Richerol et al. 2008).

By the end of the 1990s, BIO had Class-8 ice-breaker, the CCGS *Louis S. St-Laurent* that could be used to sample within the ice-infested channels of the Northwest Passage during the SHEBA and TUNDRA 99 programs (Mudie and Rochon, 2001) and in the Nares 2001 program to survey and sample surficial sediments in Nares Strait, from northern Baffin Bay to the Arctic Ocean (Mudie et al. 2005). A salient result of the Nares 2001 program was the finding that Holocene climate changes in the North Water Polynya of Baffin Bay included several cycles of summer SST warmer and more ice free than now (Mudie et al. 2004).

Other scientific cruises or programs in which the BIO played a determinant role notably include: The Joint Western Arctic Climate Study Program (JWACS), during which sampling took place in 2002 on the Mackenzie shelf and trough; The Canadian-lead international programs Canadian Arctic Shelf Exchange Study (CASES) andf ArcticNet, during which sampling took place in 2005-2005 in the Beaufort Sea, Amundsen Gulf and along the main axis of the Northwest Passage.

TUNING THE KEYS

Initial studies of arctic dinoflagellate distributions and their environmental affinities (Mudie 1992; Mudie and Harland 1996) were either based on empirical matching of key species with average water temperature and ice cover, or used multivariate statistical analyses for a relatively small array or samples from Eastern Canada. By 2001, however, more accurate quantitative records of changes in SST for both summer and winter, and in SIC (as months per year with >50% sea ice) could be constructed from statistical fine-tuning of a huge database of circum-Arctic and subarctic dinoflagellate cyst assemblages. Data from the tops of box-core samples at 677 arctic and subarctic sites (de Vernal et al. 2001; Mudie and Rochon 2001) were calibrated against the oceanographic data to develop paleoclimatic transfer functions using the biogeographical closest analogue method (Best Analogue Method, now the Modern Analogue Technique). For this study, log-transformed data for 54 dinocyst species grouped into 40 taxa were used, and the reconstructed values are the weighted average of the 10 best analogues. The accuracy of the estimated SST is ± 1.3°C and 1.7°C for winter and summer, respectively, and ±1.1 months/year for the SIC.

EAST-WEST CLIMATE CHANGE DURING THE HOLOCENE

Geological archives for the Northwest Passage. A transect of cores collected during various research cruises provide a glimpse of the paleoceanographic changes that took place in the Canadian Arctic within the last 11,700 years. These cores were collected at key locations along the Northwest Passage and approaches (Fig. 1). Holocene sediment accumulation throughout the Canadian Arctic Archipelago is heterogeneous and accumulation rates are generally in the order of 10 to 180 cm per thousand years, providing decadal-scale temporal resolution. The sediments in most marine channels consist of laminated glaciomarine silty clay of varying thickness overlaid by a relatively thin layer of recent (Holocene) sediments. The chronological framework is based on ^{210}Pb measurements on sediments, AMS-^{14}C ages (on mollusk shells) and on correlations with well-dated reference curves using high-resolution paleosecular variation records of the Earth's geomagnetic field. The details on the chronology are reported elsewhere (Barletta et al. 2008, 2010; Ledu et al. 2008, 2010a, b; Lisé-Pronovost et al. 2009). High accumulation rates of Relatively thick Holocene marine sediments accumulations were recorded only in very localized deep basins, and sedimentological analyses indicated that sedimentation was uninterrupted throughout the studied time interval.

The marine record from the eastern Canadian Arctic is represented by studies of dinoflagellate cysts in cores that were collected in Jones Sound and Barrow Strait (Fig. 2). The Jones Sound sequence covers the last 6700 cal BP, while the Barrow Strait core spans the last ~11,000 cal BP. The dinoflagellate cysts show that the early Holocene (from 11,000 to ~6000 cal BP) in Barrow Strait is characterized by relatively frigid conditions, with SST estimates as low as 2ºC colder than modern conditions. Such harsh conditions are associated with the retreat of the Innuitian and Laurentide ice sheets which continued until ~8000 and 6800 cal BP respectively (Dyke 1999; England et al. 2006; Carlson et al. 2008), and were important sources of cold meltwater in this area. During this interval, the estimated duration of SIC varies between +1 and -1 month/year of sea ice compared to modern conditions. Following the early Holocene maximum solar insolation, which peaked around 9000 BP (Berger 1978), arctic climate conditions improved during the middle Holocene, a period known as the Holocene thermal maximum. The Holocene thermal maximum timing and amplitude is variable in time and space (e.g. Renssen et al. 2009). In Jones Sound, dinoflagellate cysts indicate that maximum SSTs were reached around 6000 cal BP (Fig. 2), with estimates ~2 to 3.5ºC warmer than modern conditions, while in Barrow Strait, SST estimates ~1ºC warmer than today were recorded around 4500 BP. A cooling trend observed only in the Jones Sounds area was recorded from 6000 cal BP, when SST decreased steadily in a series of warm and cold oscillations with a periodicity of 1818 years (Rochon et al. 2006).

The central-western Arctic Holocene paleoceanographic record is represented by a marine sequence from Dease Strait (Fig. 2) that spans from ~8000 to 1000 cal BP (Ledu et al. 2010a). Sea surface conditions in Dease Strait are characterized by a series of cold and warm oscillations throughout the time period covered by the core. Temperatures 1ºC warmer and down to 2ºC colder with respect to modern conditions were inferred from dinoflagellate cyst assemblages and these warm/cold spells lasted between ~750 and 1200 years each. The most recent cold spell, which lasted from 2200 to 1000 cal BP is also the coldest one with temperatures down to 2ºC colder than modern conditions. The sea ice estimates indicate that most of the time period covered by the core was characterized by +1 to 1.5 month/year of sea ice, with the exception of two very brief intervals with less sea ice at 3800 and 3000 cal BP.

In the western Arctic, the early Holocene of the Beaufort Sea (from ~9000 to 5000 cal BP) was characterized by a series of temperature oscillations 0.5ºC colder and 0.4ºC warmer with respect to modern conditions. The late Holocene sea surface conditions were marked by a temperature increase of ~1ºC, which is well within the natural variability at this site.

Opposite East-West climate trends. The most salient feature of the paleoceanographic records presented here is the presence of East-West climatic gradients expressed by opposite sea surface parameters trend between Baffin Bay and the Beaufort Sea. In the East, the Jones Sound record displays a cooling trend that started at ~6000 BP. Such a cooling trend has been observed in several other marine and continental records from the eastern Arctic (e.g. Alley et al. 1999; Smith 2002; Kerwin et al. 2004; Kaufman et al. 2009). On the opposite, the western Arctic depicts conditions warmer than present throughout the Holocene with a slight warming trend and SIC decrease in the late Holocene. Another important feature are the temperature oscillations recorded in the eastern Arctic. The Jones Sound core displayed a 1818 years cycle and the central

Arctic records displayed a 750 to 1200 years cycle. Climatic oscillations at various timescales are a major feature of Arctic climate. The thermal regime of the Arctic Ocean was linked with the decadal variability associated with the Arctic Oscillation (Polyakov and Johnson 2006, Madhusoodanan and Bijoy 2011). The Arctic Oscillation was also identified as a mechanism responsible for changes in the wind patterns, and consequently the ice drift regime in the Arctic at multidecadal to century timescales (e.g. Darby et al. 2001; Darby and Bischof 2004). In the present study, we have associated the variability of eastern and central Arctic early Holocene sea surface conditions with a strong positive mode of the Arctic Oscillation at millennial timescales, followed by the dominance of the negative mode of the Arctic Oscillation during the late Holocene (Ledu et al. 2010b). More recently, new marine sediment core data from the Beaufort Sea suggest that the Pacific Decadal Oscillation might also contribute in part to the climate patterns (Ledu et al. submitted, Durantou and Rochon submitted) and enhanced phytoplankton productivity in the Beaufort Sea area. The temporal resolution of the sampling in most marine sediment cores was insufficient to record the modern warming trend. However, decadal-scale sea surface condition reconstructions in three short sediment cores from the Beaufort Sea (Richerol et al. 2008) indicated that the actual warming trend started prior to the beginning of the industrial era in this region. This is consistent with the millennial-scale warming trends observed in longer time series from the western Arctic, but does not allow linking the sea surface temperature increase with anthropogenic activities.

LOOKING AT THE BIG PICTURE

Overall, it is now generally agreed that there have been climate and sea ice changes in some parts of the Canadian Arctic that have been larger and faster than those recorded previously in ice cores or marine sediments (Mudie et al. 2005; Pienkowsky et al. 2011), while other areas do not record post-industrial era changes that are larger than earlier natural cycles. Clearly there is a still a lot more work to do to fully understand the complex interactions between greenhouse gas increases, short and long-term changes in solar activity or orbital movements, and the way the ocean responds to atmospheric warming.

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FIGURE LEGENDS

Figure 1. Map showing the physiography of the study area and surface currents: Dark blue arrows indicate cold water currents; red arrows indicate warm water currents. The blue dots indicate the location of marine sediment cores. The pale yellow lines indicate the main axis of the Northwest Passage and alternate routes.

Figure 2. Diagrams showing the SST and duration of SIC reconstructions for the 4 marine cores discussed in the text. The data are expressed as departure from the mean value of each parameter at the core site. The black arrows indicate increasing or decreasing trends.

Figure 1

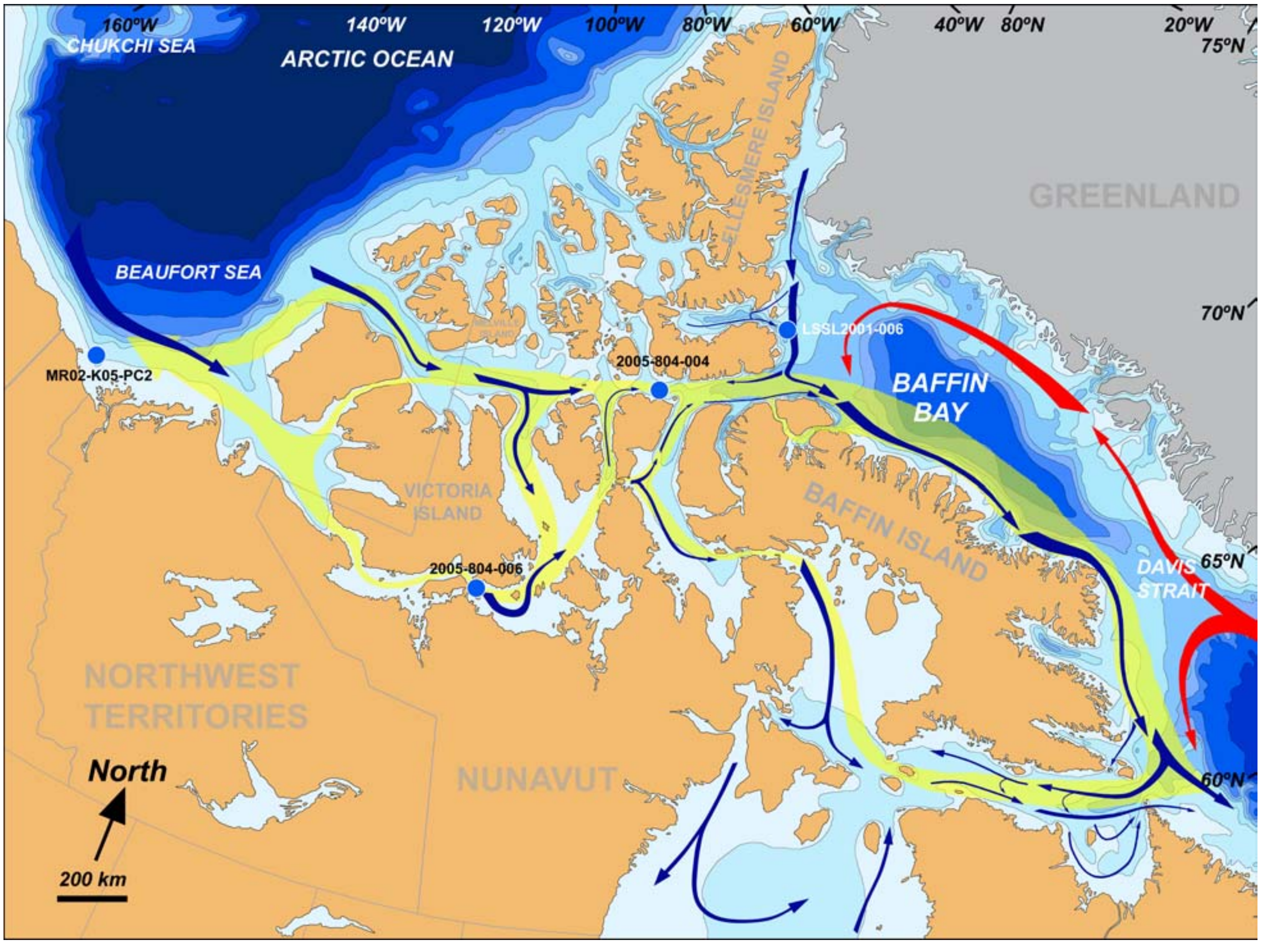
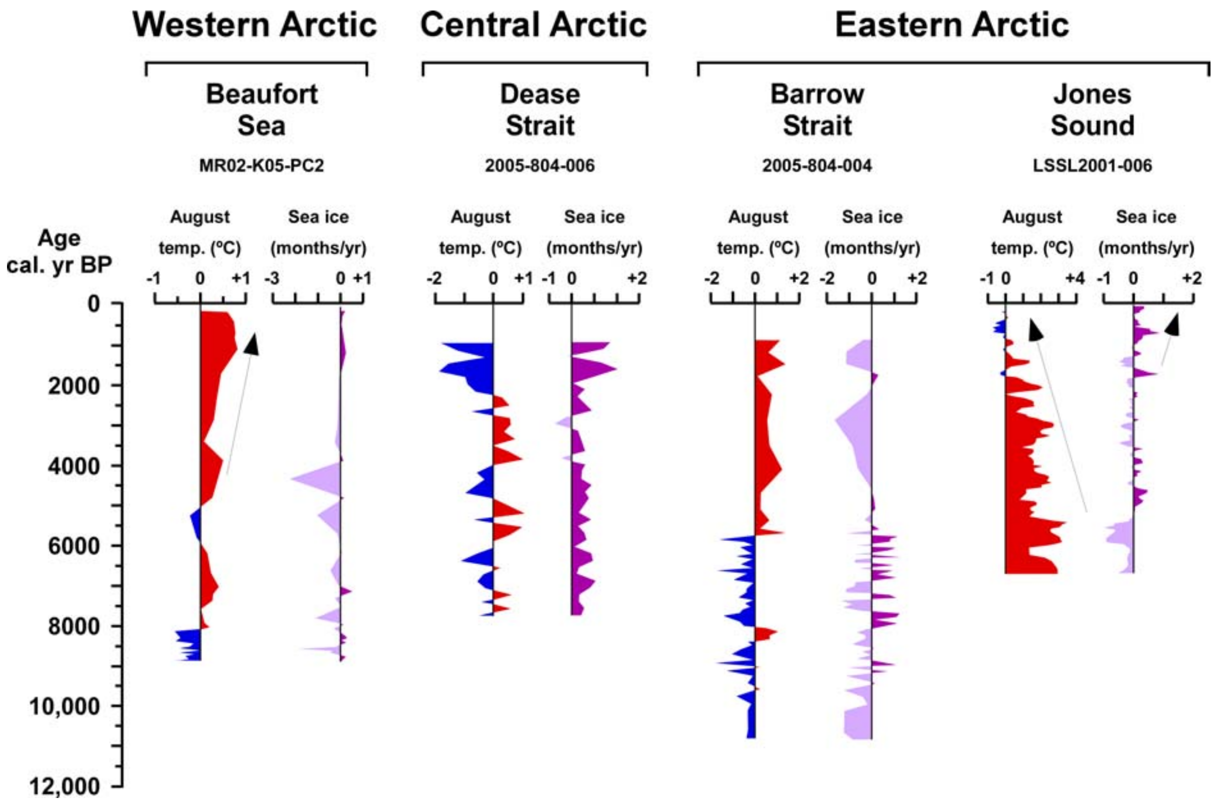

160°W
140°W
120°W
100°W
80°W
60°W
40°W
80°N
20°W
75°N
70°N
65°N
60°N
CHUKCHI SEA
ARCTIC OCEAN
BEAUFORT SEA
ELLESMERE ISLAND
GREENLAND
LSSL2001-006
2005-804-004
MR02-K05-PC2
BAFFIN BAY
VICTORIA ISLAND
BAFFIN ISLAND
DAVIS STRAIT
2005-804-006
NORTHWEST TERRITORIES
NUNAVUT
North
200 km

Figure 2


Western Arctic
Central Arctic
Eastern Arctic
Beaufort Sea
MR02-K05-PC2
Dease Strait
2005-804-006
Barrow Strait
2005-804-004
Jones Sound
LSSL2001-006
Age cal. yr BP
August temp. (ºC)
Sea ice (months/yr)
-1 0 +1
-3 0 +1
-2 0 +1
-1 0 +2
-2 0 +2
-2 0 +2
-1 0 +4
-1 0 +2
0
2000
4000
6000
8000
10,000
12,000